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(54) **SYSTEMS AND METHODS FOR CONTROLLING A COMPRESSOR RECIRCULATION VALVE**

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See application file for complete search history.

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(57) **ABSTRACT**

Systems and methods to control compressor recirculation of a reactant in a fuel cell system. A recirculation valve flow setpoint value for a gas flow to the recirculation valve is calculated based on a received cathode flow setpoint. A value corresponding to a predicted recirculation valve position is generated, and can be used as a control command for changing the position of the recirculation valve to reduce the valve response time during operational transients of the fuel cell system.
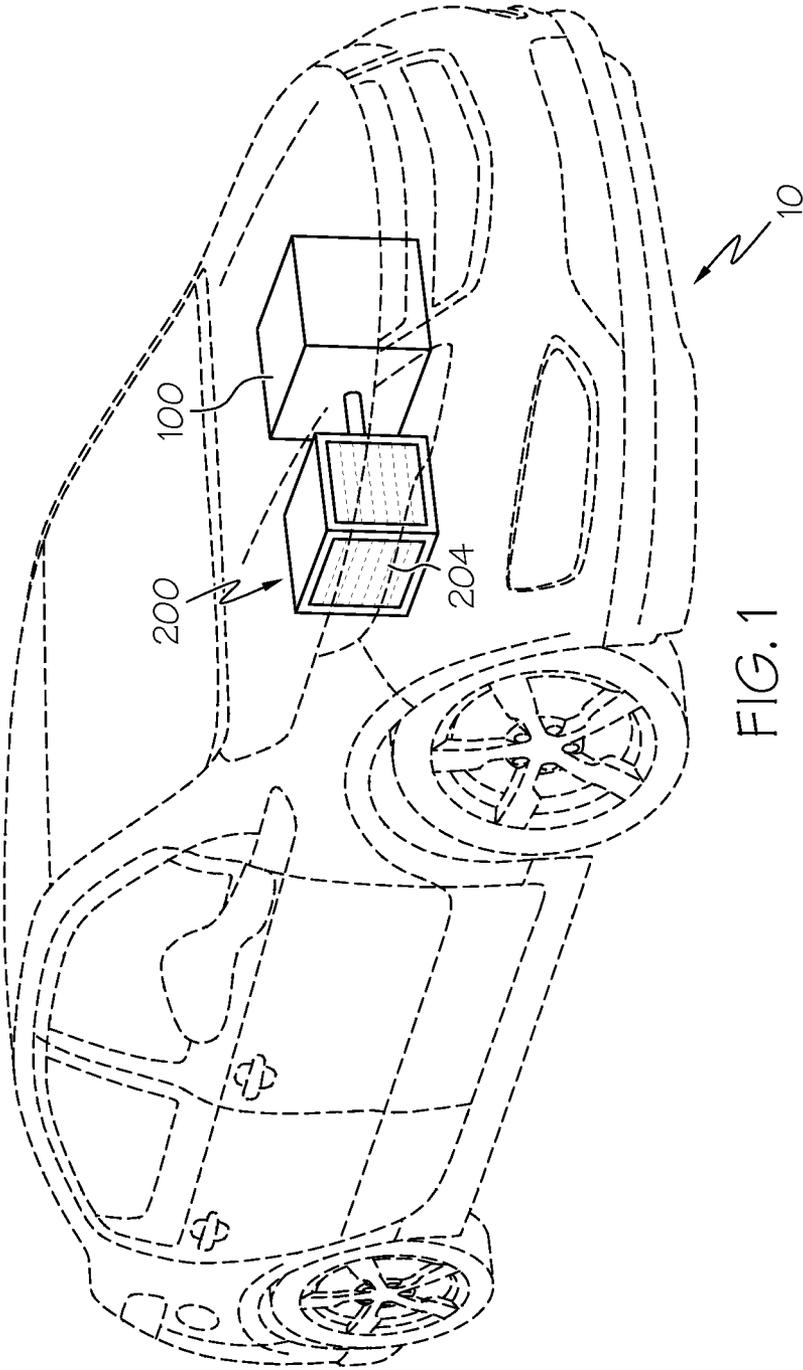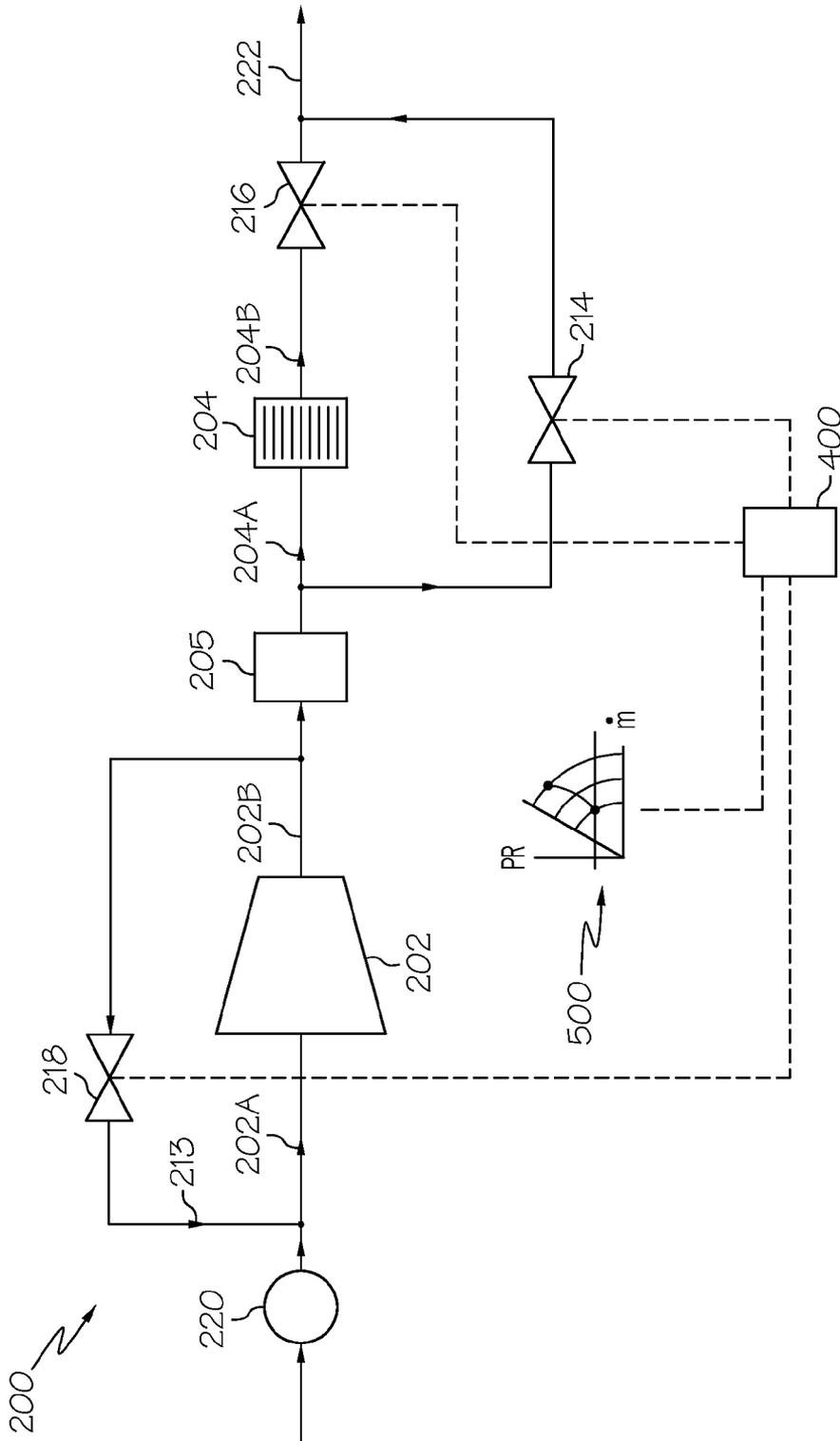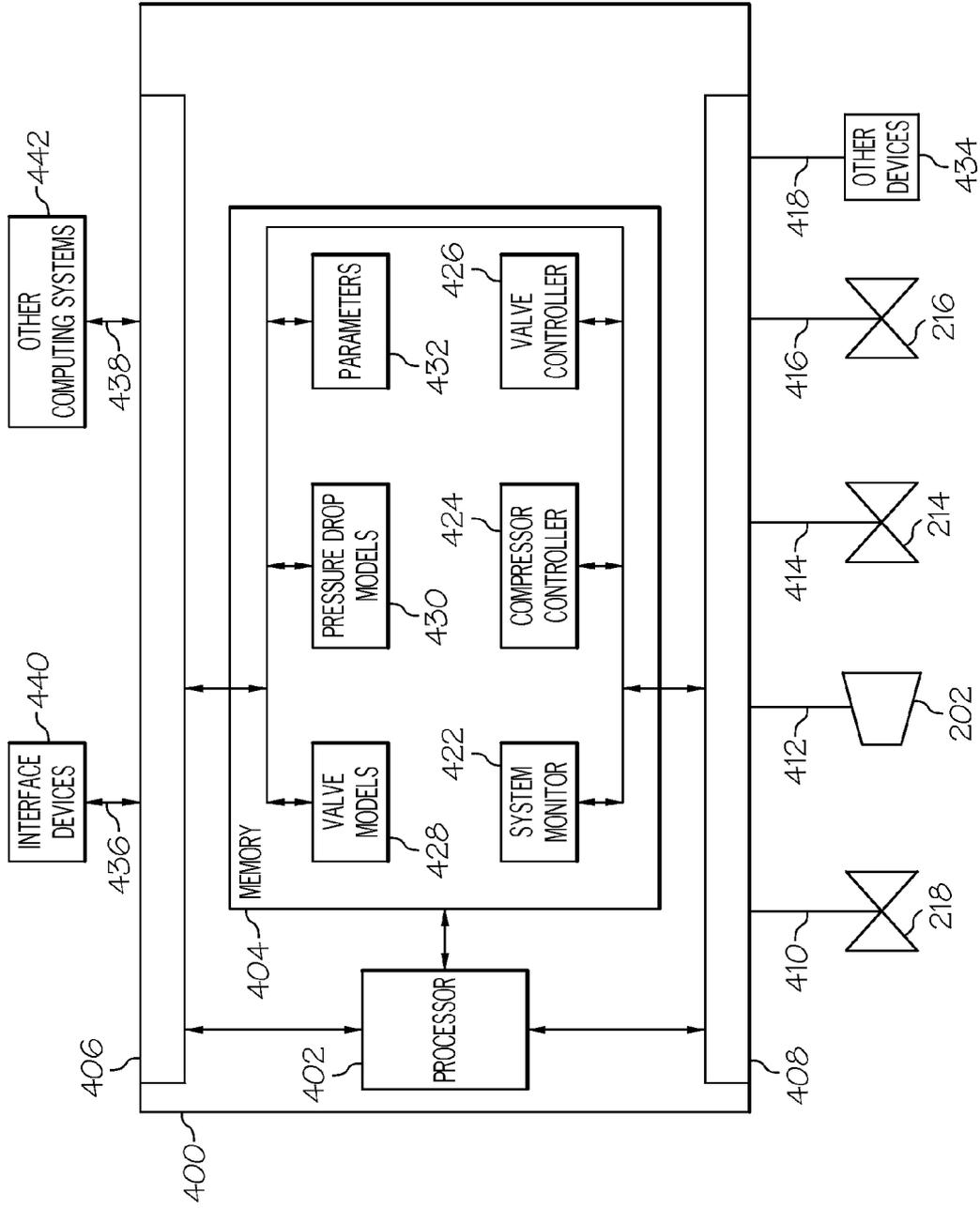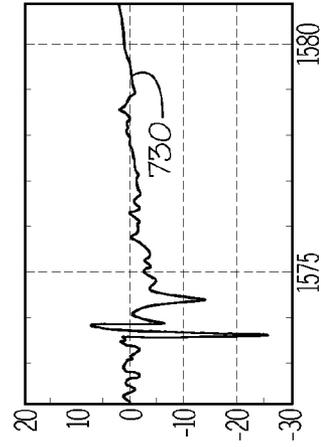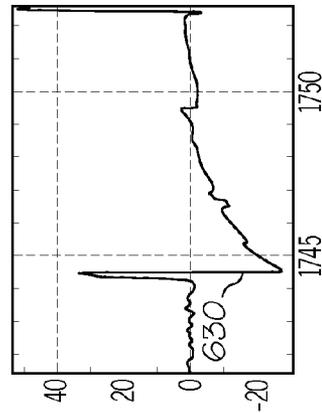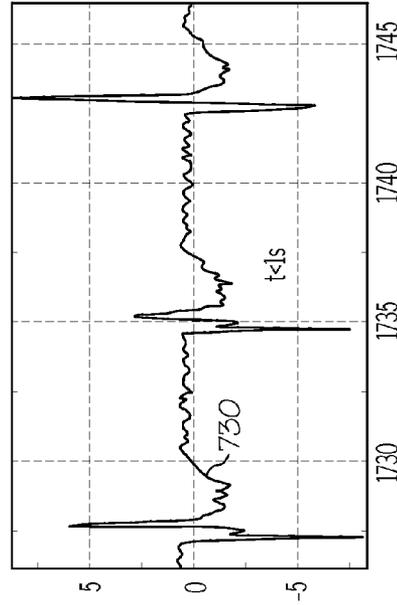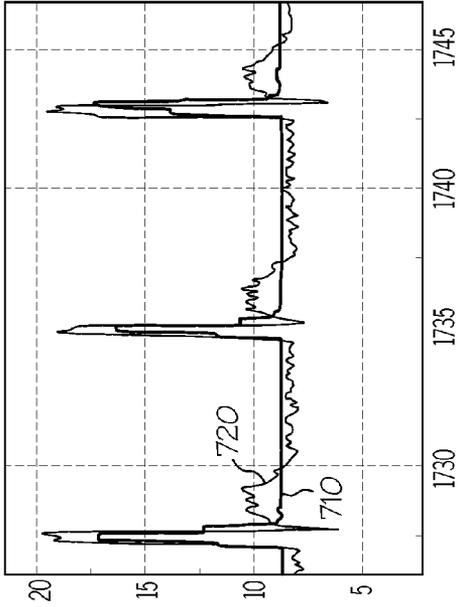
20 Claims, 6 Drawing Sheets

FIG.1

FIG. 2

FIG. 3
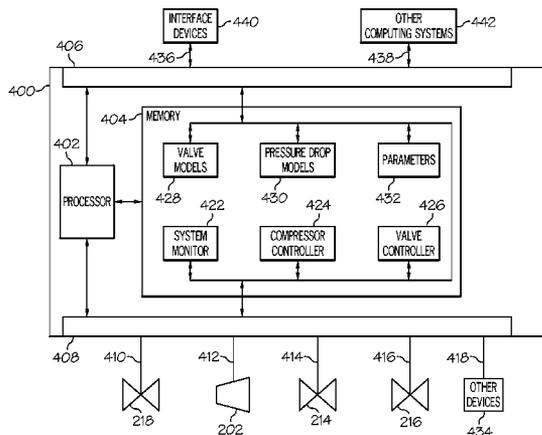
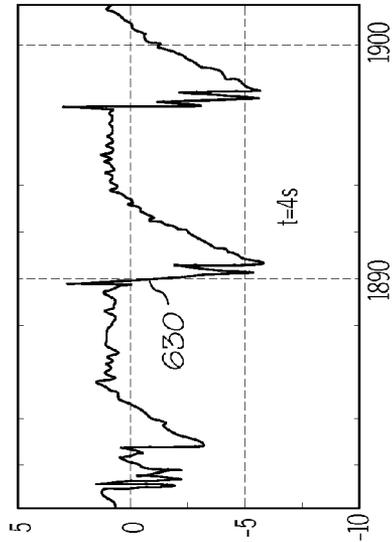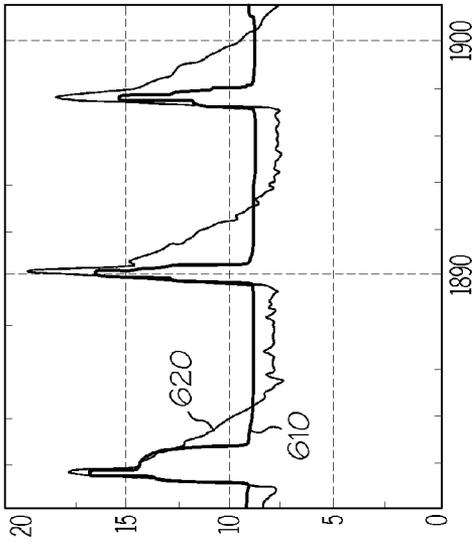FIG. 4
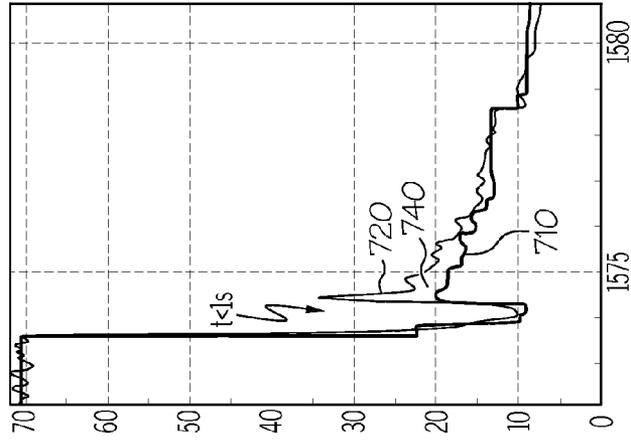
FIG. 5B
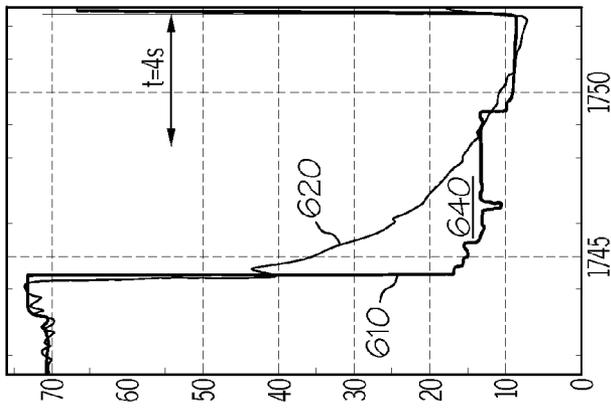
FIG. 5A
(PRIOR ART)

FIG. 6B

FIG. 6A
(PRIOR ART)

SYSTEMS AND METHODS FOR CONTROLLING A COMPRESSOR RECIRCULATION VALVE

BACKGROUND OF THE INVENTION

The present application relates generally to controlling a compressor recirculation valve in a vehicle fuel cell system, and more particularly to systems and methods for controlling a compressor recirculation valve to help meet a fuel cell stack cathode flow setpoint, especially during transient operating conditions.

Automotive technology is rapidly expanding in the area of finding alternatives to using gasoline as the primary source of energy in vehicle propulsion systems. One area of interest in recent years has focused on utilizing gaseous reactants as fuel. Gases, such as hydrogen, provide a promising alternative to gasoline because of their abundance in nature. In some vehicular systems, propulsion may be achieved by using hydrogen gas as part of a chemical reaction within a fuel cell to generate electrical energy that can be used to power an electric motor. The generated electricity can then be used to propel the vehicle through the motor, either alone or in conjunction with a petroleum-based combustion engine. Such fuel systems also typically produce less pollution than petroleum-based ones.

In a typical fuel cell, hydrogen or another reactant gas is supplied to the anode of the fuel cell, where the hydrogen is broken into electrons and positively charged ions. An electrolyte layer separates the anode from the cathode, allowing the ions to pass to the cathode, while preventing electrons from passing to the cathode. Instead, electrons are routed around the electrolyte layer through a load and back to the cathode, allowing electrical power to be harnessed. At the cathode, the ions, electrons, and supplied oxygen or air are typically combined to produce water and heat. Individual fuel cells may be arranged in series or parallel as a fuel cell stack in order to produce a higher voltage or current yield. Furthermore, still higher yields may be achieved by combining more than one stack.

In a vehicle utilizing fuel cell technology, these reactant gases may be transported and used within a pressurized gas system. For example, stored hydrogen may be provided to a fuel cell anode and chemically reacted to generate an electrical current. Similarly, air may be received by an air intake and provided to the cathode of a fuel cell. Such vehicle fuel cell systems require the use of compressors to perform such pressurizing function, and may additionally include ancillary equipment such as valves, controllers or the like to regulate the flow of a reactant gas between the compressor and fuel cell.

An inherent attribute of such compressors (at least as they relate to cathode-side operation) is that the cathode's pressure control and flow control are coupled together. Such coupling tends to destabilize system operation, especially during periods of transient system operation. These concerns are particularly acute during transient operating conditions, where both the flow setpoint and the pressure setpoint may exhibit near-instantaneous changes. Even more particularly, the difficulties of ensuring proper recirculation flow are especially acute during downtransient operation, as the inertial effects of a compressor being asked to slow down prevent the compressor speed from dropping as fast as needed; this in turn has a propensity for causing a recirculation flow mismatch. Because the water production in a fuel cell stack varies with current, a downtransient event (where the stack current is suddenly reduced) causes a concomitant rapid drop of the

water production. If stack cathode air flow is not reduced along with this current reduction, the stack will quickly dry out, resulting in damage to it. Likewise, the mismatch can also be due to not enough flow being delivered to the cathode. In this case, the presence of a recirculation valve may cause too much recirculation may take place, which results in stack flooding. As such, merely having a recirculation valve does not—in and of itself—ensure quick, precise control to avoid both stack overflow dryout and stack underflow flooding.

SUMMARY OF THE INVENTION

The invention disclosed herein works towards stabilizing the system to minimize both the dryout and flooding conditions mentioned above. In one embodiment, a method for controlling a compressor recirculation valve for a vehicle fuel cell system is disclosed, where the recirculation valve fluidly connects the outlet of the compressor to an inlet of the compressor. The method includes receiving as input a stack cathode flow setpoint for a gas flow being supplied to a fuel cell cathode from a compressor output. The method further includes calculating a recirculation valve flow setpoint value (also known as a predicted or desired value) using operational data from the compressor and the stack cathode flow setpoint. The method additionally includes generating a recirculation valve control command that causes the recirculation valve to change positions. By such a method, a compressor flow setpoint can be used to calculate a recirculation flow setpoint by, for example, taking a difference between the compressor flow setpoint and the stack cathode flow setpoint. This provides a predicted recirculation valve flow value.

In one optional form, the method takes place during an operational transient of the fuel cell system. In an even more particular optional form, the operational transient is a downtransient, where the power generated by the fuel cell changes from high to low, as does the need for oxygen or a related cathode reactant being delivered to the fuel cell stack. Thus, in the event of a downtransient, the method may be used to predict the future recirculation valve position needed to meet the new stack cathode flow setpoint, as well as to send a command to the recirculation valve in order to meet such new setpoint. As such, calculations performed in accordance with the present disclosure are preferably used in a predictive capacity to decide a future valve position. Feedforward terms, such as the stack cathode flow setpoint and compressor outlet pressure setpoint, may be used, while other operational parameters (in particular, feedback parameters such as the compressor speed that typically changes relatively slowly) may be used too. Significantly, feedforward control of the compressor recirculation valve helps to stabilize and control this inherently coupled system. In one form, the control described herein may be used in conjunction with feedforward compressor speed control that is addressed in companion application Ser. No. 13/660,073 entitled PREDICTIVE CATHODE COMPRESSOR SPEED CONTROL IN A FUEL CELL POWER SYSTEM which is filed on the same day as the present application and incorporated in its entirety by reference. In the present context, the relative speed with which a component (such as the compressor) changes does not imply a slow transition, but rather that such transition takes place over a length of time that—if not corrected—could lead to deleterious humidity imbalances within the stack. For example, a downtransient for the physical compressor speed from a maximum to a minimum might be about 4 seconds; this is a rather long time for the cathode membranes of the stack to be subjected to the drying effects of the larger airflow. The prompt operation of the recirculation valve

as discussed herein meliorates the impact of the excess air flow during this transition period. Compressor operational data may be derived from a compressor map; such data may be placed into a conventional machine-readable form, such as through a lookup table or the like that uses known compressor characteristics provided by the compressor manufacturer. In a particular form, a compressor inlet gas flow setpoint may be the type of operational data that may be determined from the compressor map. In a like manner, the recirculation valve flow setpoint value may be calculated using a difference between the compressor inlet gas flow setpoint and the stack cathode flow setpoint. Likewise, the stack cathode flow setpoint may be generated elsewhere, such as in another algorithm that may be stored on a computer or related controller. In another optional form, the recirculation valve flow setpoint value is used to calculate the new recirculation valve position, which will be treated as a feedforward term for the valve position setpoint. In addition, a proportional-integral-derivative (PID) controller is used to generate the compensational term for the new valve position, which is treated as the feedback term of the new valve position since it is based on the stack cathode flow feedback value and it tries to eliminate the error (or difference) between the stack cathode flow setpoint and the stack cathode flow feedback value. As such, the new valve position is the sum of the feedforward (i.e., open-loop) term and the feedback (i.e., closed-loop) term, and the controller will command the valve with a recirculation valve control command to change the position to the new setpoint. It will be appreciated by those skilled in the art that the new valve position, even though it may utilize feedback information (such as compressor speed or pressure or temperature) may not use flow feedback information since that is the target control term.

In another embodiment, a controller for a vehicle fuel cell system is disclosed. The controller includes at least one processor and a non-transitory memory, where the latter stores machine instructions executed by the former to cause the controller to determine a cathode flow setpoint for gas flow supplied by an outlet of a compressor to a cathode of one or more fuel cells that are used to form a stack of fuel cells in the fuel cell system. A compressor map (which may be stored in RAM or ROM of the memory) that includes data corresponding to the operation of the compressor may be accessed by the processor in order to help it perform one or more calculations pertaining to recirculation valve settings. The instructions also cause the processor to calculate a flow value for the recirculation valve such that gas flow to the recirculation valve from the outlet of the compressor takes into consideration the stack cathode flow setpoint and compressor map data.

Optionally, operational data corresponding to the compressor map is contained within the non-transitory memory. The compressor map data can be accessed by the controller to determine a gas flow setpoint for the compressor inlet. The instructions may also be used to have the processor calculate a difference between the compressor inlet gas flow setpoint and the cathode flow setpoint as a way to determine the value needed for the recirculation valve to be set to. As mentioned above, in addition to the setpoint and related feedforward information, the algorithm used to control valve position may employ feedback terms. Preferably, a control signal generated by the controller can be sent to an actuator in order to reposition the valve in a more open or closed configuration commensurate with the needs of the vehicular fuel cell system.

In another embodiment, a vehicular fuel cell system is disclosed. The system includes a fuel cell including a cathode

and a compressor having an inlet and an outlet. The outlet is operatively connected to the cathode of the fuel cell and provides gas to the cathode of the fuel cell. The system also includes a recirculation valve operatively connected to the inlet and the outlet of the compressor. The system further includes a controller having at least one processor and a non-transitory memory in signal communication with the processor. The memory stores instructions that, when executed by the processor, cause the processor to determine a cathode flow setpoint for a gas flow to the cathode. The instructions further cause the processor to use operational data pertaining to the compressor that can be stored in the form of a compressor map. The instructions also cause the processor to calculate a recirculation valve flow value for a gas flow to the recirculation valve using the compressor map and the cathode flow setpoint; this in turn may be used to generate a recirculation valve control command that causes the valve to change positions.

Optionally, the compressor map is used to determine a gas flow setpoint to the compressor inlet. The instructions may further cause the processor to calculate a difference between the compressor inlet gas flow setpoint and the cathode flow setpoint as a way to determine the recirculation valve value, which in an even more particular form, may constitute a feedforward value for the controller. As stated above, the position of the recirculation valve may be determined by the feedforward value, and may additionally be based on one or more of a feedback-based integral value and derivative value. Data communication equipment (for example, signal-carrying wires, connectors or the like) may also form part of the fuel cell system; such equipment may be used to convey the recirculation valve control command between at least the controller and the recirculation valve.

BRIEF DESCRIPTION OF THE DRAWINGS

The following detailed description of specific embodiments can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. 1 shows a vehicle having a fuel cell system;

FIG. 2 is a schematic illustration of the air supply system in the vehicle fuel cell system shown in FIG. 1;

FIG. 3 is an illustration of a compressor map;

FIG. 4 is a schematic illustration of a controller for the vehicle fuel cell system of FIG. 1;

FIG. 5A shows a flow control for a downtransient according to the prior art;

FIG. 5B shows a flow control for a downtransient according to the present disclosure;

FIG. 6A shows a flow control for an uptransient according to the prior art; and

FIG. 6B shows a flow control for an uptransient according to the present disclosure.

The embodiments set forth in the drawings are illustrative in nature and are not intended to be limiting of the embodiments defined by the claims. Moreover, individual aspects of the drawings and the embodiments will be more fully apparent and understood in view of the detailed description that follows.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As stated above, the use of compressors within vehicular fuel cell systems presents additional challenges for the automotive industry, where flow rate, as well as the related fuel

cell cathode stoichiometry, is an important parameter for such a system. Cathode stoichiometry is defined as the ratio of inlet molar flow rate of a reactant to rate of consumption of the reactant, and therefore is directly proportional to gas flow to the cathode. When the output of the fuel cell goes from high power to low power (for example, during an idle state), there is less reactant consumption, which in turn increases the cathode stoichiometry significantly. However, this increase in stoichiometry may dry out the stack and accordingly impact the stack performance or even causes damages to the stack. In any event, providing quick opening and closing of the recirculation valve according to the aspects of the invention will improve the chance of the system to meet the flow setpoint quickly and avoid a stack overstoichiometry condition; these more precise instructions are especially beneficial during downtransient conditions, where the latency associated with compressor speed decreases may otherwise hamper maintaining proper stack stoichiometry.

Referring now to FIG. 1, vehicle 100 is shown, according to embodiments shown and described herein. Vehicle 100 (e.g., a car, bus, truck or motorcycle) is powered by one or more fuel cells that make up fuel cell system 102 that converts stored gaseous fuel into electric power for engine 104. In a preferred embodiment, fuel cell system 102 is a hydrogen-based fuel cell system that converts a catalytic reaction between hydrogen gas and oxygen into electric current. Fuel cell system 102 may include one or more onboard hydrogen storage tanks or related storage tanks (neither of which are shown), the latter such that onboard reformation of a hydrogen gas precursor may take place. In such a case, fuel cell system 102 may also include any number of valves, compressors, tubing, temperature regulators, electrical storage devices (e.g., batteries, ultra-capacitors and the like, none of which are shown) and controllers to help ensure proper operation of fuel cell system 102. Engine 104 may be a fully electric or a hybrid electric engine (e.g., an engine that uses both electricity and petroleum-based combustion to propel vehicle 100). In either configuration, engine 104 utilizes the power from fuel cell system 102 for at least a portion of the propulsion needs of vehicle 100.

Any number of different types of fuel cells may be used in fuel cell system 102 (e.g., metal hydride fuel cells, alkaline fuel cells, electrogalvanic fuel cells or any other type of known fuel cells). Multiple fuel cells may also be combined in series or parallel within fuel cell system 102 as a fuel cell stack in order to produce a higher voltage or current yield by fuel cell system 102. The produced electrical power may then be supplied directly to engine 104 or stored within an electrical storage device for later use by vehicle 100.

Referring now to FIG. 2, a schematic illustration of fuel cell system 102 is shown, according to embodiments shown and described herein. Compressor 202 receives air at inlet 202A, compresses it, and provides the supplied gas via outlet 202B to cathode inlet 204A of fuel cell stack 204, where the gas is used to produce electrical power for vehicle 100. Exhaust gas or liquids are then removed from cathode outlet 204B via exhaust 222. In addition to compressor 202, fuel cell system 102 also includes a number of valves that help to regulate the flow of gas throughout the system. For example, fuel cell system 102 may include a bypass valve 214 that allows some or all of the gaseous fuel to bypass fuel cell stack 204. Fuel cell system 102 may also include cathode backpressure valve 216 that regulates the flow of exhaust from cathode outlet 204B. Cathode backpressure valve 216 may be used, for example, to control the pressure and flow of gas through the cathode. Recirculation valve 218 allows for selective fluid connection between compressor outlet 202B and inlet 202A.

An especially valuable use for recirculation valve 218 is during operational transients in the fuel cell stack 204, where it can increase or decrease the amount of air present at the inlet 206 depending on the transient needs of the stack 204.

Fuel cell system 102 further includes a number of sensors that measure the characteristics of the gas within the system. For example, fuel cell system 102 may include flow meter 220 that measures the mass air flow from the air intake system. Other non-limiting examples of sensors (not shown) in fuel cell system 102 include sensors that measure the mass air flow, pressure, temperature, density or the like, of the gas or gases used in fuel cell system 102. Further examples include sensors that measure the position of valves 214, 216, 218 and the speed of compressor 202.

A downtransient can occur in the fuel system 102, meaning the output of the fuel cell stack 204 shifts to a lower power setting based on a request from an operator of vehicle 100. In one example, a lower power setting may correspond to idle state operation of vehicle 100. In order to maintain stability of stack 204, the cathode stoichiometry must be increased, but in such a way as to not adversely impact other operational parameters of stack 204. According to the present disclosure, the recirculation valve 218 can be opened at outlet 202B of compressor 202. It is to be noted that control over one device in the system 102 may be integrated into the control over another device. For example, a setpoint may be used to control several valves of the system 102. In a more particular form, an algorithm used as part of the present disclosure may help determine a flow setpoint for compressor 202 that is to be used to calculate the recirculation flow setpoint that would be equal to the difference between the flow setpoints of compressor 202 and the stack 204. The logic of the present method of controlling recirculation valve 218 is especially beneficial when used in conjunction with power downtransients in fuel cell system 102. In one form, the compressor flow setpoint information may be derived from a compressor map 500.

Referring now to FIGS. 3 and 4, more details associated with compressor map 500 and the various features of controller 400 are shown. Referring with particularity to FIG. 3, data contained in the compressor map 500 is that which corresponds to the operation of the compressor 202; such information may include pressure ratios for given flow conditions (including, for example, factors pertaining to mass flow that may additionally take into consideration atmospheric temperature and pressure variations) at various speed lines 505. Compressor maps 500 provide a useful tool to predict the behavior of compressor 202 by allowing the prediction of flow setpoints based on the operating state of the compressor 202. Typically, a compressor map 500 relates the pressure ratio 502 to the flow 504 of the gas through the compressor 202. A surge line 506 delimits those compressor 202 operating states that result in stalls, flow reversals and other undesirable surge condition from those that do not, where points to the left of surge line 506 are problematic, while operating points to the right of surge line 506 correspond to generally normal compressor 202 operation. The distance between an operating point 508, 510 or 514 (discussed in more detail below) of the compressor 202 and surge line 506 is referred to as the surge margin, and provides a measure of how close the compressor 202 is to a surge condition. In one form, the data that corresponds to the various operational conditions across the compressor map 500 may be stored in a lookup table or related data structure that may in turn be embedded or otherwise contained within any suitable machine-accessible medium, such as a preprogrammed chip or memory device, flash memory, hard disk drive, CD, DVD, floppy disk or related non-transitory structure. Thus, such machine-acces-

sible medium may be in the form of a memory **404** that forms part of the controller **400**. The data in the compressor map **500** may be pre-loaded into the controller **400** using information provided by, for example, the manufacturer of the compressor **202**. In another form, the data can be built using a diagnostic routine that varies the operation of the compressor **202** and detects various conditions; either form is acceptable. In addition to the feedforward setpoint parameters mentioned above, the compressor **202** may be additionally controlled by one or more feedback loops in order to regulate its speed, differential pressure, gas flow rate or related parameters in order to try to maintain the one or more setpoints.

As mentioned above, points **508**, **510** and **514** illustrate various operating conditions (or points) that may be experienced by the compressor **202**. For example, the compressor **202** is operating at a feedback speed at point **508**. If the output of the fuel cell system goes to low power, a downtransient condition may exist. The compressor **202** speed may then be controlled to point **510** in order to conserve resources, as both the x-axis flow rate **504** and y-axis pressure ratio **502** experience a corresponding decrease. Likewise, the compressor **202** speed may be controlled along one of the constant speed lines **505** to point **514**, as the rotational speed of compressor **202** goes down slowly during a downtransient condition. In such a circumstance, the gas flow setpoint of the compressor inlet **202**A at point **514** is determined by the pressure ratio setpoint **502** and the feedback speed at point **508**. The recirculation valve **218** flow setpoint value can be calculated from the difference between the gas flow setpoint of the compressor inlet **202**A and the cathode flow setpoint shown at point **510**. The recirculation valve **218** can then be opened to reroute any surplus air flow rather than have such air pass through the cathode of stack **204** where, as stated above, it could result in a mismatched stoichiometry for stack **204**. As will be understood by those skilled in the art, a preferred maximum operating point "A" for the compressor **202** is at the top of the uppermost of speed lines **505** that intersects with point **508**. The inertia within compressor **202** makes it hold its last speed for a bit of time during the downtransient; this causes the compressor flow to trend towards operation point "C" at point **514** on the map **500**.

With regard to the particular example shown in FIG. 3, a transient condition from point **508** (high power) to **510** (lower power) on the map **500** means the stack cathode flow setpoint correspondingly changes; likewise the compressor outlet **202**B pressure setpoint is changed as shown as moving from point **508** to point **510**. Since the flow setpoint is changed, the position of the recirculation valve **218** to meet the new flow request at point **510** needs to be predicted and then promptly adjusted. Because compressor **202** running characteristics are already known (and—as mentioned above—generally slowly-changing, especially over the duration of the downtransient) by following certain characteristics, the compressor map **500** may be used to predict the recirculation valve **218** position with the simplifying assumption that the speed of compressor **202** is unchanged over the course of a single time step. Additional operational knowledge may also be relied upon. For example, knowing that the pressure at compressor outlet **202**B will drop if the recirculation valve **218** is opened allows opening the recirculation valve **218** to the predicted position so that the compressor can run at the point **514**. The flow of air to be bypassed by the recirculation valve **218** in order to meet the new stack cathode flow setpoint **514** is equal to the difference between it and point **510**.

From this, the feedforward term of the new recirculation valve **218** position is then determined by a general valve model by using the flow through the valve (i.e., the difference

between the x-axis points at points **514** and **510**), the flow temperature, the pressure at the valve **218** inlet and outlet, as well as other necessary inputs. Together with the feedback term determined from the PID controller, the new position of the recirculation valve **218** is finally determined after which recirculation valve **218** will be instructed to move to the new position and the compressor **202** will run at point **514** while its pressure at the outlet **202**B will be dropped to the pressure at setpoint **514**. Under such an exemplary move, the compressor **202** flow is indicated at point **514**, while the fuel cell stack **204** flow is at point **510**. Accordingly, the bypassed (i.e., through the recirculation valve **218**) flow is the difference between points **514** and **510**, shown as Δ_{ISP}. From this, the decrease of the rotational speed of compressor **202** results in its operating condition moving from point **514** to point **510**. During this process, the stack **204** flow and pressure both continue to meet the new setpoint **510**. The feedforward term of the new valve position ensures to open the valve **218** quickly during downtransient and close quickly during uptransient, while the feedback term of the new valve position from the PID controller **400** can eliminate any offset error or mitigate any overshoot during a transient condition. The method of the present disclosure will make the transient happen more quickly thereby avoiding drying out the stack **204**. An important side benefit of the recirculation valve **218** is that it helps prevent the compressor **202** from running into the aforementioned surge condition treatment of which is addressed in companion application Ser. No. 13/660,083 entitled REACTIVE COMPRESSOR SURGE MITIGATION STRATEGY FOR A FUEL CELL POWER SYSTEM and filed on the same day as the present application. If the system **102** is in steady state, the recirculation valve **218** will move to a position based on surge control to prevent the compressor **202** from moving above surge line **506**. The valve **218** will recirculate a minimum flow rate while the compressor **202** stays at the lowest necessary speed to achieve the desired flow.

Referring with particularity to FIG. 4, controller **400** for regulating operation of compressor recirculation valve **218** includes a processor **402**, which may be at least one processor (e.g., a microprocessor, an application specific integrated circuit (ASIC), field programmable gate array, or the like) is communicatively coupled to memory **404** and interfaces **406** and **408** (which may correspond to input and output steps, respectively). Processor **402** can (among other things) determine a cathode flow setpoint for gas flow supplied by compressor **202** to fuel cell stack **204**, where the cathode flow setpoint corresponds to a desired operating condition of the stack **204**, and the desired operating condition may be calculated at different modes. The desired operating condition may be communicated to a memory **404** for storage of the condition. In one form, the desired operating condition may be stored in a memory **404** as a lookup table, data structure or related configuration. Memory **404** may be any form of memory capable of storing machine-executable instructions that implement one or more of the functions disclosed herein, when executed by processor **402**. For example, memory **404** may be a RAM, ROM, flash memory, hard drive, EEPROM, CD-ROM, DVD, other forms of non-transitory memory devices, or any combination of such memory devices. The controller **400** may also include one or more of digital signal processing capability, application specific integrated circuitry, programmable logic devices as well as discrete gate or transistor hardware components. In this way, the controller **400** may generate and store non-transitory signals that can be used to control recirculation valve **218** positioning through one or more of the feedforward values mentioned above, as well as from feedback (i.e., integral/derivative) terms. System

operation can be affected through valve **218** opening or closing in response to the valve control command from controller **400**.

In a preferred form, at least a portion of controller **400** is configured to function as a feedforward-based device, in that the operation of one or more of the valves shown in FIG. **2** in the system (including recirculation valve **218**) is based on mathematical models or related characterization of the fuel cell system **102**, where program elements corresponding to such models can be loaded into memory **404**. In this way, by combining the mathematical model of the operation of parts or all of the fuel cell system **102** into the algorithm in controller **400**, appropriate control actions may be taken by the controller **400** based on known system parameters (such as those being sensed, measured or otherwise fed into the algorithm). As stated above, optimization of the operation of fuel cell system **102** may be enhanced by combining feedforward elements with some feedback-based elements, as the feedforward control is preferred for quickness in transitions, while the feedback is needed to reduce minor steady state errors.

Controller **400** communicates with various devices in fuel cell system **102** and, in some cases, provides either direct or indirect control over devices such as recirculation valve **218**, compressor **202** and other components. Controller **400** also receives, either directly or indirectly, sensor measurements from fuel cell system **102** to monitor the operation of the system. For example, controller **400** may receive temperature, pressure, flow, density, valve position, speed or other measurements from sensors associated with compressor **202**, recirculation valve **218**, or the like. In addition, controller **400** may also receive sensor readings from other devices (such as flow meter **220**, sensors associated with other valve **214**, **216** or the like). It should be appreciated that any number of different combinations of sensors and sensor configurations may be used, without deviating from the principles or teachings of the present disclosure.

Connections **410**, **412** and **414** may be any combination of hardwired or wireless connections that provide connections between controller **400** and compressor **202**, recirculation valve **218**, cathode backpressure valve **216**, bypass valve **214** and other devices. In some embodiments, connections **410**, **412** and **414** are part of a shared data line that conveys measurement data to controller **400** and control commands to the devices of fuel cell system **102** connected to controller **400**. In yet other embodiments, connections **410**, **412** and **414** may include one or more intermediary circuits (e.g., other microcontrollers, signal filters, etc.) and provide an indirect connection between controller **400**, compressor **202**, recirculation valve **218** and other devices **434**.

Interface **408** is configured to receive measurement data and to transmit control commands to recirculation valve **218**, compressor **202**, and other devices. For example, interface **408** may include one or more wireless transceivers, if any of connections **410**, **412** and **414** are wireless connections. Interface **408** may also include one or more wired ports, if any of connections **410**, **412** and **414** are wired connections. Interface **408** may also include circuitry configured to digitally sample or filter received measurement data. For example, interface **408** may sample temperature received from a temperature sensor of compressor **202** via connection **412** at discrete times (e.g., k, k+1, k+2, etc.) to produce discrete temperature values (for example, T(k), T(k+1), T(k+2), etc.).

In some embodiments, controller **400** may also communicate with interface devices **440** (e.g., a display, a speaker, a printer, or any other electronic device that provides or receives data to and from a user) via connection **436**. Controller **400** may also communicate with other computing systems **442** (e.g., another controller, a portable electronic device, a server, or the like) via connection **438**. Connections **436** and **438** may be wired or wireless connections. For example, other computing systems **442** may include a server located remotely from vehicle **100** and connection **422** may be a wireless connection. For example, server **400** may communicate status condition information to the server via a cellular, WiFi, radio, satellite connection, or the like. Interface **406** may also include one or more transceivers configured to send and receive location information for vehicle **100**. For example, interface **406** may include a GPS receiver or cellular receiver that utilizes triangulation to determine the location of vehicle **100**. In other embodiments, interfaces **406** and **408** may be a single interface for controller **400**.

Controller **400** uses the setpoints for the pressure ratio, surge margin or flow rate to regulate recirculation valve **218**, as well as the other valves. For example, controller **400** may determine a requested valve position for recirculation valve **218** that moves the operating state of compressor **202** away from the surge line of compressor map **50**. Controller **400** then generates a recirculation valve control command that causes recirculation valve **218** to open or close accordingly.

Parameters **432** that may alter the functions of controller **400** may include one or more threshold values for the speed of compressor **202**, temperature thresholds, or a surge condition time limit. These parameters **432** may also include values that enable or disable functions of controller **400**. For example, such parameters **432** may include those that determine if surge mitigator is active. Likewise, the parameters **432** may further include values that determine how information about fuel cell system **102** is conveyed to interface devices **440** or to other computing systems **442** (for example, how often, what format, and the like).

In some cases, some or all of parameters **432** may be pre-loaded into memory **404** (e.g., by the manufacturer of controller **400**, the manufacturer of vehicle **100**, or the like). In other cases, some or all of parameters **432** may be provided to controller **400** via interface devices **440** or other computing systems **442**. Further some or all of parameters **432** may be updated or deleted via interface devices **440** or other computing systems **442**.

Although controller **400** is shown as a singular device, it is to be understood that this is merely exemplary and is not intended to be limiting. For example, processor **402** may include any number of processors of any number of computing devices that execute the instructions stored in memory **404**. Likewise, memory **404** may include any number of memory devices and is not limited to memory devices located within the same housing as processor **402**. In some cases, processor **402** or memory **404** may even be located external to vehicle **100**.

Recirculation valve **218** flow setpoint value is calculated using the compressor map **500** and the cathode flow setpoint. As stated above, this flow setpoint value corresponds to a predicted flow, and all such calculations are for the prediction. By being a predictive parameter, this flow value has the ability to reduce the time and uncertainty associated with operational transients. A compressor inlet **202A** gas flow setpoint is determined by the compressor map **500** at a speed and pressure ratio across the compressor **500**. For example, the compressor pressure ratio setpoint PR^{Sp} may be calculated as:

$$PR^{Sp} = \frac{p_{CmprOut}^{Sp}}{p_{CmprIn}^{Sp}}$$

where $p_{CmprOut}^{Sp}$ is the pressure setpoint at the outlet **202B** of the compressor **202** and p_{CmprIn}^{Sp} is the pressure setpoint at the inlet **202A** of the compressor **202**. The corrected gas flow

setpoint of compressor inlet **202A** is determined through the compressor map **500** as follows:

$$\dot{m}_{CmprDchrg}^{SpCrtd} = \text{Map}_{Cmpr}(nn_{Cmpr}^{Crtd}, PR^{Sp})$$

where $\dot{m}_{CmprDchrg}^{SpCrtd}$ is the corrected compressor inlet gas flow setpoint determined from speed and pressure ratio across the compressor **202**. The final compressor inlet **202A** gas flow setpoint is converted from the corrected value:

$$\dot{m}_{CmprDchrg}^{Sp} = \dot{m}_{CmprDchrg}^{SpCrtd} * \frac{p_{CmprIn}}{p_{ref}} * \sqrt{\frac{T_{ref}}{T_{CmprIn}^{Sp}}}$$

where T_{CmprIn}^{Sp} is the temperature setpoint at the compressor inlet **202A** from the recirculation valve **218**. The recirculation valve **218** flow value is calculated using a difference between the final compressor inlet **202A** gas flow setpoint ($\dot{m}_{CmprDchrg}^{Sp}$) (and the stack cathode flow setpoint ($\dot{m}_{CmprAssmDchrg}^{Req}$).

$$\dot{m}_{RcrcVlv}^{Sp} = \dot{m}_{CmprDchrg}^{Sp} - \dot{m}_{CmprAssmDchrg}^{Req}$$

The recirculation valve **218** flow setpoint value ($\dot{m}_{RcrcVlv}^{Sp}$) is truncated to zero if the final compressor inlet **202A** gas flow setpoint ($\dot{m}_{CmprDchrg}^{Sp}$) is less than the stack cathode flow setpoint ($\dot{m}_{CmprAssmDchrg}^{Req}$).

The requested valve kVlv value for the feedforward term of the recirculation valve **218** position is calculated based on the valve model for subcritical gas flow as:

$$kVlv_{CmprRcrcVlv}^{Req,Subcrtcl} = a * \frac{\dot{m}_{RcrcVlv}^{sp}}{M_{CaSplyAir}} * \sqrt{\frac{M_{CaSplyAir} * T_{CmprOut}}{\left(p_{CmprOut}^{Sp}\right)^2 - \left(p_{CmprIn}^{Sp}\right)^2}}$$

and calculated as follows for critical gas flow as:

$$kVlv_{CmprRcrcVlv}^{Req,Crtcl} = b * \frac{\dot{m}_{RcrcVlv}^{sp}}{M_{CaSplyAir}} * \sqrt{\frac{M_{CaSplyAir} * T_{CmprOut}}{\left(p_{CmprOut}^{Sp}\right)^2}}$$

where $M_{CaSplyAir}$ is the molecular weight of the gas through the recirculation valve **218**, $\dot{m}_{RcrcVlv}^{SP}$ is the flow bypassed by the recirculation valve **218** calculated previously, $T_{CmprOut}$ is the temperature at the outlet **202B** of the compressor **202**, $p_{CmprOut}^{Sp}$ is the pressure setpoint at the outlet **202B** of the compressor **202**, p_{CmprIn}^{Sp} is the pressure setpoint at the inlet **202A** of the compressor **202**, and a and b are the coefficients from the unit conversion for the subcritical and critical gas flow, respectively. In some embodiments, a and b are equal to 4.633 and 5.375, respectively. The maximum of the subcritical and critical gas flow values can then be used as the requested position of the recirculation valve **218**:

$$kVlv_{CmprRcrcVlv}^{Req} = \text{Max}(kVlv_{CmprRcrcVlv}^{Req,Subcrtcl}, kVlv_{CmprRcrcVlv}^{Req,Crtcl}).$$

The final kVlv value of the valve **218** is calculated from the feedforward kVlv value calculated above and the feedback kVlv from the PID controller **400** and it is converted to the new valve position through a lookup table or other method based on the valve characteristic. The recirculation valve command is then generated and sent through interfaces **406** that cause the recirculation valve **218** to change positions. The command is generated by one or both of a feedback-based

(i.e., an integral-derivative) value and a feedforward-based (i.e., setpoint) value that is particularly well-suited to quick transient flow response.

By the above valve equations, the predicted position of recirculation valve **218** as a feedforward term to the PID controller **400** is calculated based on a valve model with the input of predicted flow, temperature, pressure and other inputs. In a particular form, the invention uses the information stored in the compressor map **500** to calculate the feedforward term of the position of valve **218**, which upon instruction from controller **400** can make the valve **218** move quickly during down or up transients compared with a purely feedback-based control strategy. It will be appreciated by those skilled in the art that the above equations are exemplary, and that other equations may be used to produce the predicted position of valve **218**; such other equations, to the extent that they are used to help predict future recirculation valve **218** position to meet the flow setpoint of fuel cell stack **204**, are within the scope of the present disclosure.

Referring next to FIGS. **5A**, **5B**, **6A** and **6B**, results of recirculation valve flow control according to the prior art (FIGS. **5A** and **6A**) and the present disclosure (FIGS. **5B** and **6B**) are shown. Referring with particularity to FIG. **5A**, differences in the stack flow setpoint **610** and stack flow feedback **620** show up as error **630**, while the dryout area **640** between the stack flow setpoint **610** and stack flow feedback **620** is large for a significant amount of time (approximately 4 seconds as shown); this can lead to a drying out of the various cathodes of stack **204** of FIG. **2**. Referring with particularity to FIG. **5B**, the differences in the stack flow setpoint **710** and stack flow feedback **720** are resolved promptly; this in turn means that the dryout area **740** is minimized, which equates to reduced cathode dryout, and improved stack performance and durability. Referring with particularity to FIG. **6A**, the cathode stack flow setpoint **610** momentarily increases, followed by a quick decrease. This is done in conjunction with anode hydrogen bleed events where anode water and nitrogen are momentarily "burped" from the system. Similar to FIG. **5A**, FIG. **6A** shows dryout areas **640** for the cathode where the stack flow setpoint **610** and feedback **620** are separated, whereas in FIG. **6B**, the disclosed invention remedies the situation by having setpoint **710** and stack flow feedback **720** correlate much better, thereby reducing the dryout area **740**.

While the present disclosure has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the disclosure as defined by the appended claims.

What is claimed is:

1. A method for controlling fuel cell system cathode stoichiometry during an operational transient with a compressor recirculation valve, the method comprising:

identifying an operational transient in a fuel cell stack;

receiving a stack cathode flow setpoint for gas flow supplied by an outlet of a compressor to a cathode of said fuel cell stack;

calculating a recirculation valve flow setpoint value for said supplied gas flow using compressor operational data and said stack cathode flow setpoint;

calculating a feedforward term corresponding to a new recirculation valve position by using said recirculation valve flow setpoint value;

generating a feedback term corresponding to said new recirculation valve position through a PID control strategy based on an error between said stack cathode flow setpoint and said feedback term; and

generating a recirculation valve control command based on said feedforward term and said feedback term that causes actuation of said recirculation valve to maintain cathode stoichiometry during said operational transient.

2. The method of claim **1**, wherein said operational transient is an operational downtransient.

3. The method of claim **2**, wherein a compressor inlet gas flow setpoint is determined from a compressor map.

4. The method of claim **3**, wherein said recirculation valve flow value is calculated using a difference between said compressor inlet gas flow setpoint and said cathode flow setpoint.

5. The method of claim **1**, further comprising using a controller for at least one of said receiving, calculating and generating.

6. The method of claim **1**, further comprising using a controller for said generating said feedback term.

7. The method of claim **1**, further comprising opening or closing said recirculation valve in response to said generated recirculation valve control command.

8. A vehicular fuel cell system cathode stoichiometry controller comprising:

at least one processor; and

a non-transitory memory in communication with said at least one processor, wherein said memory stores machine instructions that, when executed by said at least one processor, cause said at least one processor to:

identify an operational transient in a vehicle fuel cell stack;

receive a stack cathode flow setpoint for gas flow supplied by an outlet of a compressor to a cathode of said fuel cell stack;

calculate a recirculation valve flow setpoint value for a gas flow to a recirculation valve from said outlet of said compressor using a compressor map and said stack cathode flow setpoint, wherein said recirculation valve fluidly connects said outlet of said compressor to an inlet of said compressor;

calculate a feedforward term corresponding to a new recirculation valve position by using said recirculation valve flow setpoint value;

generate a feedback term corresponding to said new recirculation valve position through a PID control strategy based on an error between said stack cathode flow setpoint and said feedback term; and

generate a recirculation valve control command based on said feedforward term and said feedback term that causes actuation of said recirculation valve to maintain cathode stoichiometry during said operational transient.

9. The controller of claim **8**, wherein compressor operational data corresponding to said compressor map is contained within said memory and configured such that a gas flow setpoint for said compressor inlet is determined by said controller.

10. The controller of claim **9**, wherein said instructions further cause said at least one processor to calculate a difference between said compressor inlet gas flow setpoint and said stack cathode flow setpoint to determine said recirculation valve flow setpoint value.

11. The controller of claim **9**, wherein said changed position of said recirculation valve is determined by a feedfor-

ward value and at least one of an integral value and a derivative value within said controller.

12. The controller of claim **8**, wherein said recirculation valve control command generated by said controller is in signal communication with said recirculation valve to facilitate repositioning thereof.

13. A vehicular fuel cell system comprising:

a fuel cell stack comprising a plurality of fuel cells each of which include a cathode;

a compressor having an inlet and an outlet, wherein said outlet is fluidly connected to said stack to provide a reactant gas to said cathodes;

a recirculation valve operatively connected to said inlet and said outlet of said compressor; and

a cathode stoichiometry controller comprising at least one processor and a non-transitory memory in signal communication with said at least one processor, wherein said memory stores instructions that, when executed by said at least one processor, cause said at least one processor to:

identify a transition of an output of said fuel cell stack;

receive a stack cathode flow setpoint for gas flow to said cathodes;

calculate a recirculation valve flow setpoint value for a gas flow to said recirculation valve using operational data pertaining to said compressor and said stack cathode flow setpoint; and

generate a recirculation valve control command that causes said recirculation valve to change positions valve to maintain cathode stoichiometry during said operational transient.

14. The system of claim **13**, wherein said operational data pertaining to said compressor is based on a compressor map.

15. The system of claim **14**, wherein said operational data from said compressor map is used to determine a gas flow setpoint to said compressor inlet.

16. The system of claim **13**, wherein said instructions that cause said at least one processor to calculate a recirculation valve flow setpoint value further comprise instructions to have said at least one processor:

calculate a feedforward term corresponding to a new recirculation valve position by using said recirculation valve flow setpoint value; and

generate a feedback term corresponding to said new recirculation valve position through a PID control strategy based on an error between said stack cathode flow setpoint and said feedback term.

17. The system of claim **13**, further comprising data communication equipment configured to convey said recirculation valve control command between said controller and said recirculation valve.

18. The method of claim **1**, wherein the compressor recirculation valve is configured to mitigate surge conditions when said fuel cell stack is in a steady-state condition.

19. The controller of claim **8**, wherein the compressor recirculation valve is configured to mitigate surge conditions when said vehicle fuel cell stack is in a steady-state condition.

20. The system of claim **13**, wherein the compressor recirculation valve is configured to mitigate surge conditions when said fuel cell stack is in a steady-state condition.

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